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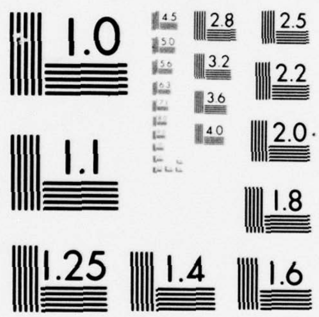

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TERMINAL BALLISTIC APPLICATION OF HYDRODYNAMIC COMPUTER CODE CALCULATIONS

J. T. Harrison
R. R. Karpp

April 1977

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USA ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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Calculational techniques which accurately simulate the functioning of conventional warheads would be powerful tools in the hands of munition designers. In this work we attempt to summarize results of applying a particular numerical method, the method programed in the HEMP code, to the simulation of fragmenting shell, Misznay-Schardin munitions, and shaped charge warheads. ~~We conclude~~ Results indicate that this technique cannot provide complete solutions to all these problems, but it can provide useful information relevant to terminal ballistics. Also, as better modeling techniques are developed, a potential exists for acquiring next page

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I. INTRODUCTION

A. Background and Summary

Many problems in terminal ballistics may be adequately described by modeling the material in a rather simple way, i.e., as a continuous, inviscid, compressible fluid or an elastic-perfectly plastic solid. However, even for these cases, the solution to problems involving two-dimensional unsteady motion must usually be obtained by approximate, numerical techniques. A computer program (HEMP), which solves this type of problem by a finite-difference technique, has been developed by the Lawrence Livermore Laboratory.[1] We have applied this code to many terminal ballistic problems, and this report summarizes some of the results.

We have not formally reported applications of this finite-difference code to explosive-metal acceleration problems since the time the code was initially checked for accuracy. Therefore, this report summarizes the current predictive capability of our version of the HEMP code with reference to the simulation of warhead performance.

Figure 1 illustrates warheads composed of explosive-metal systems of primary interest to be simulated. These are conventional warheads, including fragmenting munitions, Misznay-Schardin devices, and shaped charge munitions. Before actual applications were considered, however, preliminary test calculations were conducted to establish the accuracy with which the code solves initial boundary value problems. Also, to verify the adequacy of the material description, calculated results were compared with experimental results of problems of interest. These test problems indicate that the numerical simulations are within a 10% error bound, and therefore, calculations should provide useful information concerning warhead performance.

The fragment velocity distribution (speed and direction) from a naturally fragmenting munition can be accurately predicted by these numerical calculations. These results are generally superior to those obtained from the Gurney and Taylor formulae since the two-dimensionality of the flow is accurately treated.

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[1] *M. L. Wilkins, "Calculation of Elastic-Plastic Flow," in Methods of Computational Physics, Vol. 3, edited by Alder, Fernback and Rotenburg, Academic Press, New York and London, 1964.*

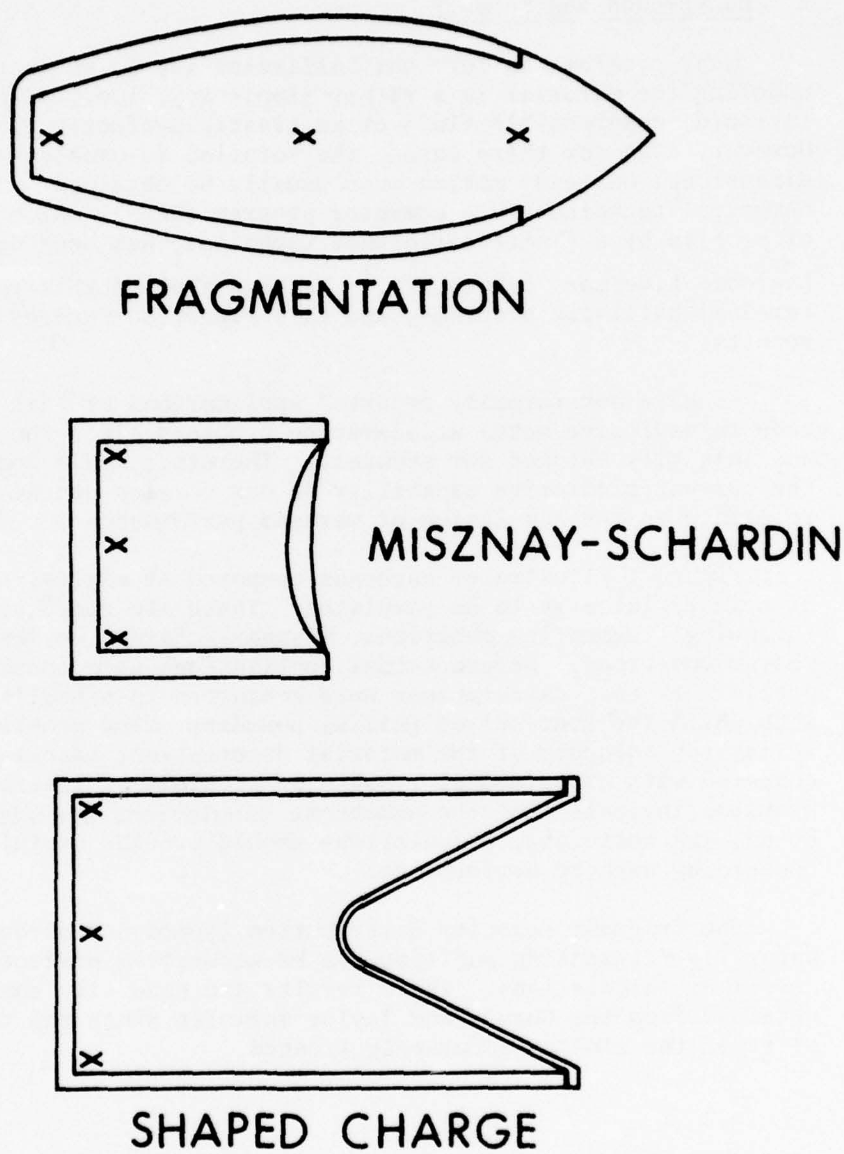

Figure 1. Illustrations of Warheads of Explosive-Metal Systems Simulated

Code calculations have also been used to simulate Misznay-Schardin devices (end projecting devices). Generally, the calculations predict the correct velocity and shape, if the liner remains intact. However, if the liner breaks up during launch, a large discrepancy between predicted and actual configurations may exist. Accurate methods to predict liner break up would increase the utility of this prediction technique.

Attempts to simulate the shaped charge warhead with this numerical method have also been made. For shaped charges with relatively wide angles, the code can accommodate the liner deformation in the initial stages of formation. These calculations can provide the tip velocity, but the deformation cannot be followed far enough in time to provide a complete description of the jet. For conventional shaped charges, these calculations cannot directly predict the jet formation; however, with slight modifications in the jet formation region, which will be discussed later, a collapse velocity distribution can be calculated. The standard jet formation equations can then be used to convert these collapse velocities to jet properties. Good agreement exists between experimental data and calculated collapse velocities; however, because of the sensitivity of the jet velocity distribution to the collapse velocity distribution, the predicted jet velocity distribution is not accurate. Therefore, this prediction technique is not considered to be successful. A better simulation could probably be obtained by rezoning the Lagrangian code or by using an Eulerian code for reasons which will be presented subsequently.

B. HEMP Code Formulation

The balance equations of mass, momentum, and energy written with respect to a coordinate system fixed in space (Eulerian) constitute the system of partial differential equations which is solved by the HEMP[1] code. Problems which can be represented by either plane flow or axisymmetric flow can be treated. The most general constitutive relation used in the code is an elastic-plastic formulation which is similar to the Prandtl-Reuss equations, except that the pressure is related to the density and internal energy by a rather general equation of state. With this formulation the motion of an inviscid gas can be treated as a special case of the general formulation. The detonation of a high explosive can be simulated by releasing energy at a rate consistent with the detonation rate of the explosive.

The problems of present interest involve the motion of a metal liner or casing which is accelerated by the pressure loading from a detonating explosive. At the gas-metal interface, the gas pressure should match the normal component of stress, and the normal components of velocity should also match. The code has a "slide line" routine which approximately satisfies this interface requirement.

The numerical solution technique is formulated by introducing a material coordinate system (Lagrangian) and calculating the motion of the node points of this mesh. Spatial derivatives are replaced by an approximation derived from a line integral definition of a derivative, and material derivatives are replaced by a centered difference approximation. The result is an explicit, conditionally stable, finite-difference system which is used to integrate the governing equations. The major drawback of this method is that the mesh may become quite distorted if large strains arise. This zone distortion can cause the allowable time step to become quite small, and the integration may not be continued past a certain point in time. Nonetheless, the method is straightforward, and material boundaries are automatically traced. Therefore, problems involving several materials present no additional difficulties.

C. Accuracy of HEMP Code Solutions

Before using this code to study and predict the performance of warheads, several test problems were numerically solved and compared with solutions obtained by other methods. These problems were chosen to determine both how well the numerical scheme solves the mathematical problem and how well it models actual physical processes. Therefore, the numerical solutions were compared with exact solutions of simple problems, and then to test the physical simulation, numerical results were compared with experimental results. This study is reported in Reference 2. The conclusion of this comparison is that the code is operating correctly and that the accuracy is sufficient to make it useful in warhead studies. The numerical technique generates solutions which agree with exact analytical solutions. Problems which are inherently two-dimensional require a finer zoning than inherently one-dimensional problems if the same quality solution is desired. Generally, if a coarse zoning is used, wave structure which appears in the exact solution tends to be smoothed, and numerical values may oscillate about the exact values. Also, solutions to problems involving essentially hydrodynamic flows appear somewhat better than solutions to problems of elastic and elastic-plastic motion. In the simulation of a detonation wave, a very fine zoning is required if the peak pressure is to approach the Chapman-Jouguet pressure. Therefore, in many actual problems, the pressure distribution applied to a metal by a detonating explosive may be somewhat smoothed and lower in peak value than the true distribution. This result causes the calculated initial response of the metal to be slower than the actual response.

[2] *R. R. Karpp, "Accuracy of HEMP Code Solutions," Ballistic Research Laboratories Memorandum Report No. 2268, Aberdeen Proving Ground, MD, January 1973. (AD #757153)*

II. SIMULATION OF CONVENTIONAL MUNITIONS

A. Fragmenting Munitions

In this section we will briefly describe the basic assumptions and calculations for fragmenting munitions. For specific details of the calculations see reference 3.

The quickest and easiest way to estimate the speed of fragments from fragmenting casings is with the Gurney Formula[4] which gives the speed as a function of the local ratio of explosive mass to casing mass. The direction of the fragments can also be quickly estimated from the Taylor Relation.[5] These two formulae rely on radial expansion of the explosive gases (for axisymmetric systems) and steady state conditions. For heavily confined systems with rather large length to diameter ratios (e.g. artillery shells, etc.) these relations give useful results. For other systems of interest, these calculated results can be improved by using finite-difference calculations. Figure 2 shows the fragment speed distribution and projection angle distribution obtained experimentally for a steel cylindrical casing filled with Octol explosive. For this test, the length to diameter ratio was two, and therefore, edge effects are important. The results of HEMP code calculations are also plotted. These calculated results agree well with the experimental data. The results of the Gurney and Taylor formulae are also shown. For this configuration, the HEMP code results correlate better with the experimental data.

Figure 3 shows the finite-difference mesh used to compute the motion of the casing. (It must be noted that some of the expanded explosive was deleted in this drawing after 25μsec). In these calculations; the strength of the casing material (steel) was considered via the elastic-perfectly plastic model. However, since it is known[6] that fragmentation of the casing occurs at an expansion ratio of about 1.75, the strength model for the casing material is replaced by a fluid model for each casing element which has expanded past this expansion ratio. The amount of explosive gas which could leak through an elemental portion of the casing, is approximated for each time step by the

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[3] *R. R. Karpp and W. W. Predebon, "Calculations of Fragment Velocities From Naturally Fragmenting Munitions," Ballistic Research Laboratories Memorandum Report No. 2509, July 1975. (AD #B007377L)*

[4] *R. W. Gurney, "The Initial Velocities of Fragments From Bombs, Shells and Grenades," Ballistic Research Laboratories Report No. 405, Aberdeen Proving Ground, MD, September 1943. (AD #AT1 36218)*

[5] *Birkhoff, MacDougall, Pugh and Taylor, "Explosives With Lined Cavities," J. Appl. Phys. 19,* 1948.

[6] *C. Hoggatt and R. Recht, "Fracture Behavior of Tubular Bombs, J. Appl. Phys.,* 39, 1856-1862, 1968.

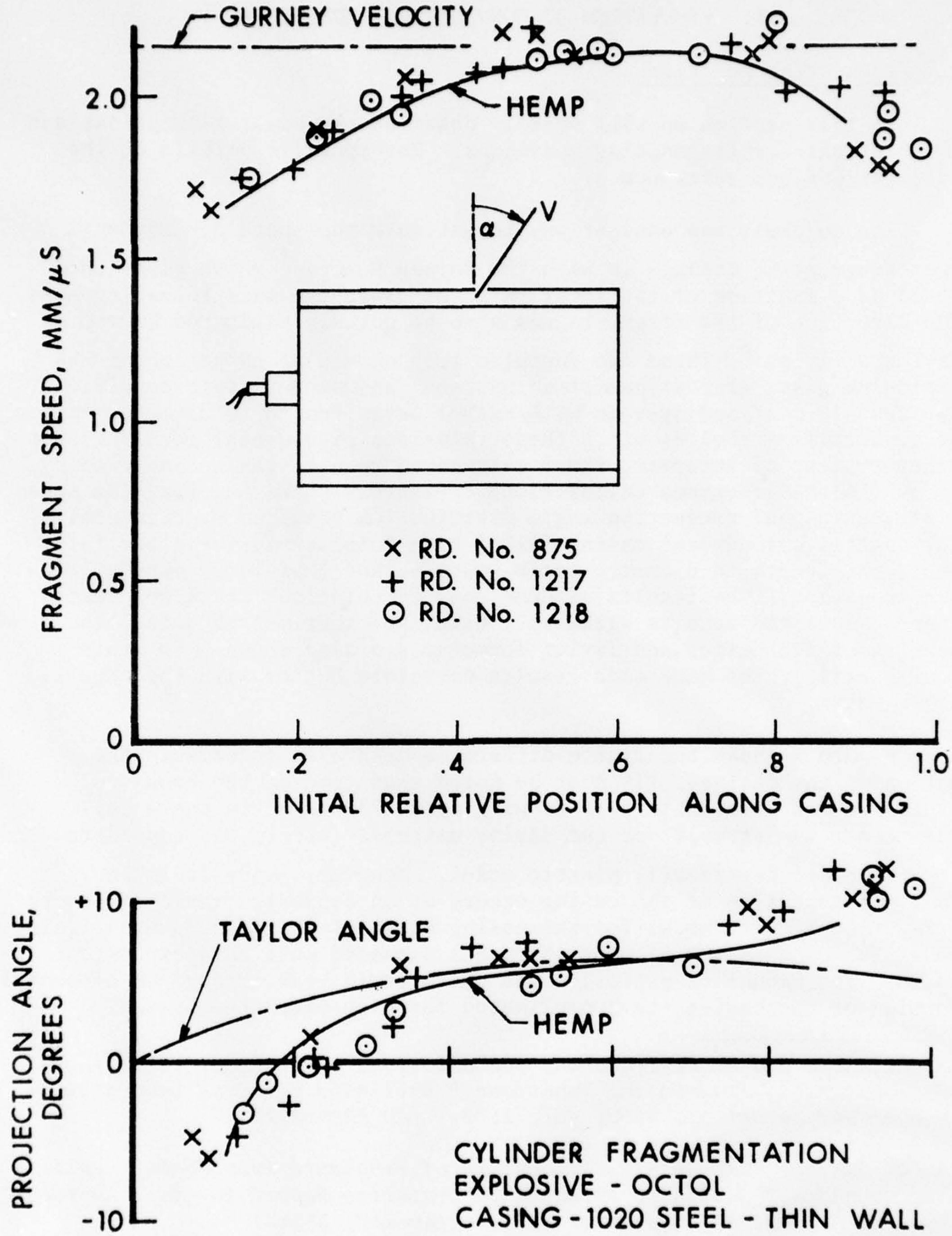

Figure 2. Fragment Velocity Distribution from a Steel Cylinder with an OCTOL Explosive Fill (L/D = 2, C/M = 8.6)

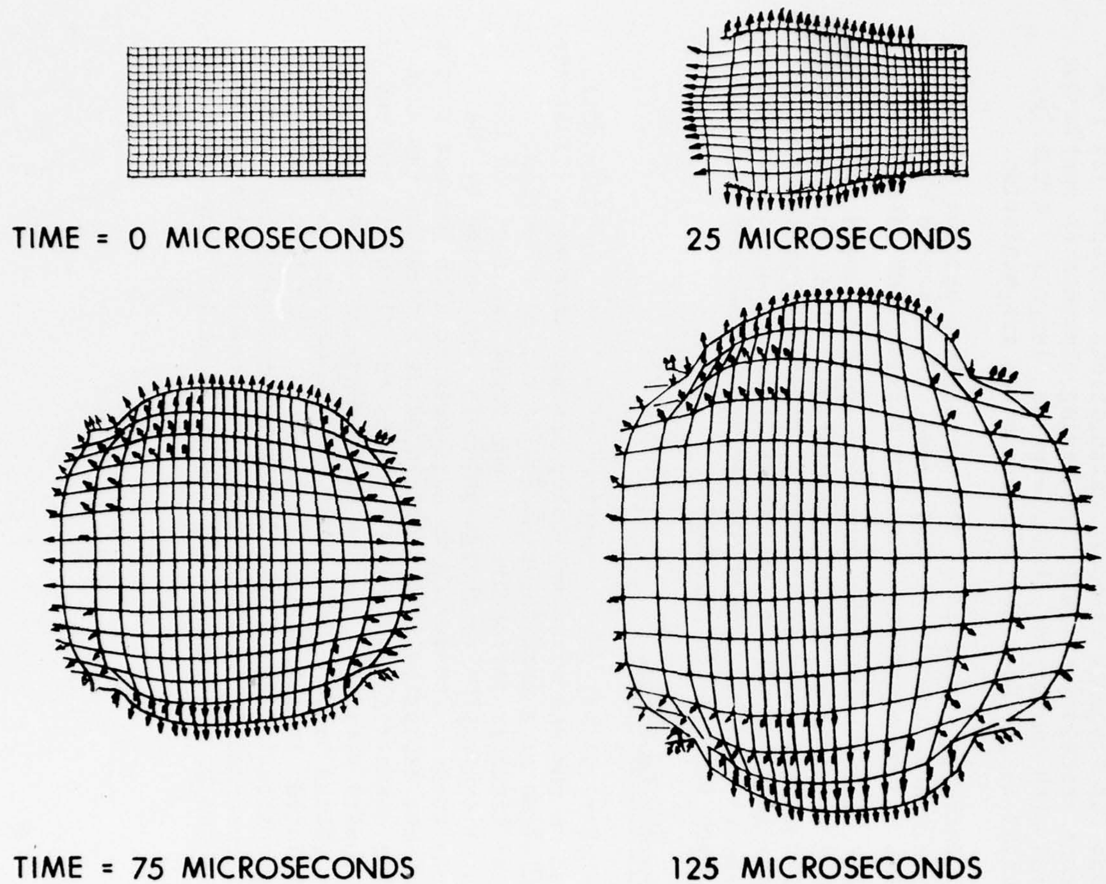

Figure 3. Stages of Expansion of an Explosively Loaded Cylinder as Computed with the HEMP Code (data shown in Figure 2)

formula for the mass flow through a nozzle. Then, the mass in the explosive zone which is in contact with this fragmented casing zone is reduced by the appropriate amount. Another modification which has been put into the code for fragment velocity calculations corrects for the fact that the code calculation treats the casing elements as continuous rings of material with increasing circumferential lengths. Actually, the circumferential length does not increase after fragmentation.

With these features in the code, the correlation between calculated results and experimental results is quite good, as indicated by Figure 2. Figures 4 and 5 show a direct comparison between HEMP calculated velocity and mass distributions and data obtained from arena tests.[7] The nose fuse was not modeled in the HEMP calculation. Thus, the fragments predicted are those of the casing at angular positions greater than 45 degrees. The agreement appears to be satisfactory. These calculations have been applied to several warhead configurations, and the results have generally been found to be reliable.

B. Misznay-Schardin Munitions

A Misznay-Schardin (MS) device consists of a liner, usually metal, which is mounted on the end of an explosive charge. Figure 6 illustrates a computer simulation of a particular MS device called a "Ballistic Disc." The metal liner is represented by the first two zones on the right hand side of the explosive charge which is represented by the remaining sixteen zones. The device is axisymmetric with respect to the center line, and the explosive is end initiated at a point on the axis of symmetry. The detonating explosive projects the plate off the end of the charge and toward a target. As the plate moves, it also deforms. The sequence of shapes assumed by the deforming liner at the indicated times after initiation is illustrated in Figure 6. The last shape was obtained radiographically from a test firing and indicates the actual shape at 375 microseconds after initiation. The result indicates that code calculatons can be used to predict the final pellet shape from a MS device.

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[7] *Firing Record No. B-11982, U.S. Army TECOM, Development and Proof Services, Aberdeen Proving Ground, MD, August 1953 to June 1954.*

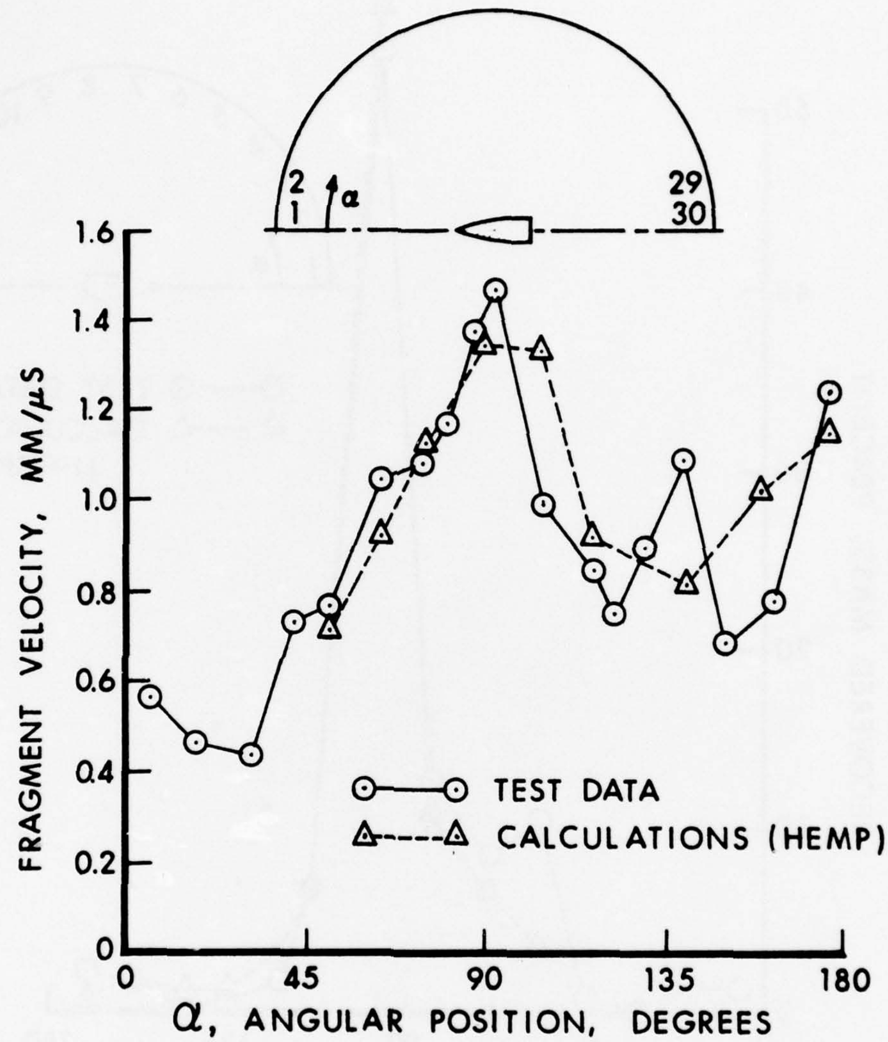

Figure 4. Comparison of the Calculated Fragment Velocity Distribution and Arena Test Data for a Typical H.E. Shell

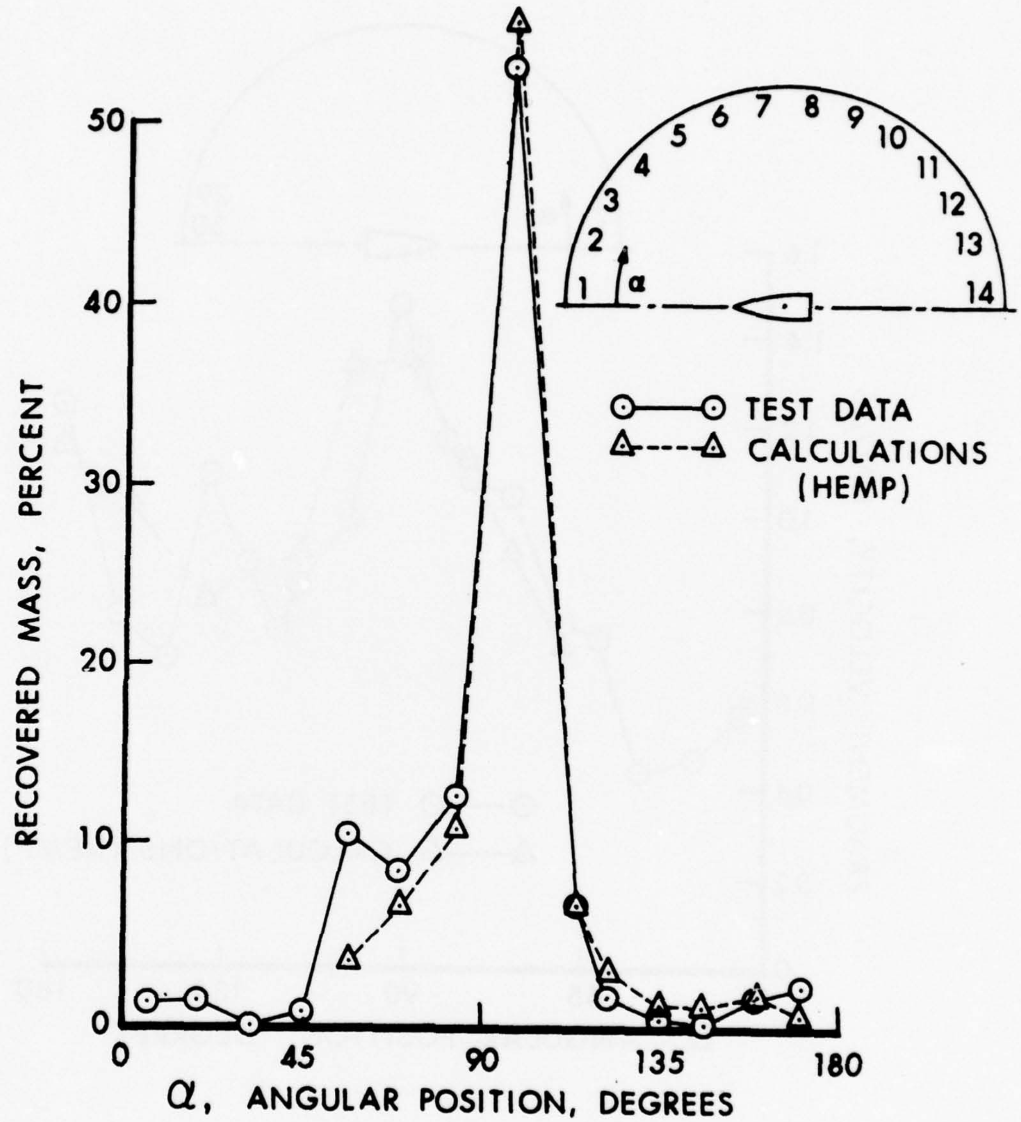

Figure 5. Comparison of the Calculated Fragment Mass Distribution and Arena Test Data for a Typical H.E. Shell

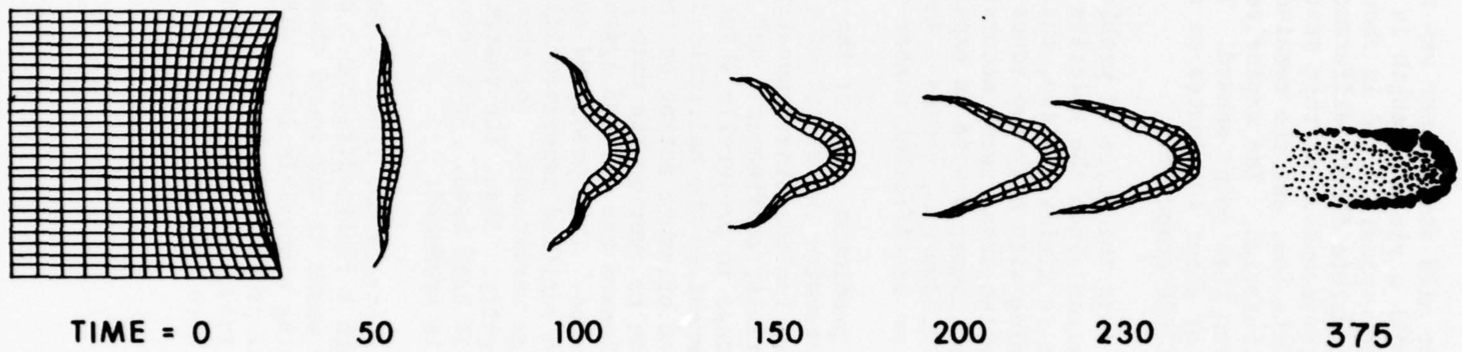

Figure 6. Computer Simulation of the Performance of a Ballistic Disc Device. (Time is in units of μsec and at 375μsec the Experimental Radiograph tracing is shown)

In this calculation, the mild steel liner was treated as an elastic-perfectly plastic material with a yield strength in tension of 0.5 GPa (about 73 ksi). Although the explosive grid is shown only for the initial configuration, the complete finite-difference calculation was carried out to about 150 microseconds. At that state of the process, the explosive pressure is quite low, and the remainder of the calculation treated only the liner material. The explosive-metal interface was treated as a free surface from that point onward. This approach resulted in a total computation time of about 40 minutes on the BRLESC computers or about one minute on a CDC7600 computer.

It should be mentioned that this type of problem is ideally suited to a Lagrangian code calculation since the relative material flow in both the liner and explosive is minimal. Also, this problem has been run with the very coarse zoning with only two zones across the liner thickness. The resulting pellet shape seems accurate, but the predicted velocity is a little low when compared with an experimental observation of a similar configuration (2.76mm/μsec versus 2.4mm/μsec). This difference may be caused by an insufficient number of zones.

Once confidence in the predicted shape of the projectile is established, one could use the code to determine the effect of a variation in design parameters. These parameters include liner geometry and materials, explosive geometry and materials, confinement, and initiation location. Figure 7 illustrates the change in projectile shape caused by adding both lateral and end confinement to the ballistic disc design. Because of confinement, the increased pressure acting on the outer portion of the liner causes this portion to overlap the main part. Also, more material is forced to flow toward the axis of symmetry resulting in large deformations in this area. This predicted configuration and the predicted velocity have been verified experimentally. Figure 8 illustrates the effects of further design variations. For this run, the liner design has been changed slightly. Also, the charge length is shortened and peripheral initiation has been used. As a result, a drastically different projectile shape is produced.

These three figures illustrate the types of parametric studies which can easily be made with a finite-difference code. This code has been used in a design study where it was found that break up or fragmentation of the liner may occur causing a possible large discrepancy between the predicted and observed final projectile shape. To avoid this shortcoming of the code, design solutions using a combined calculational and empirical design procedure were tried.

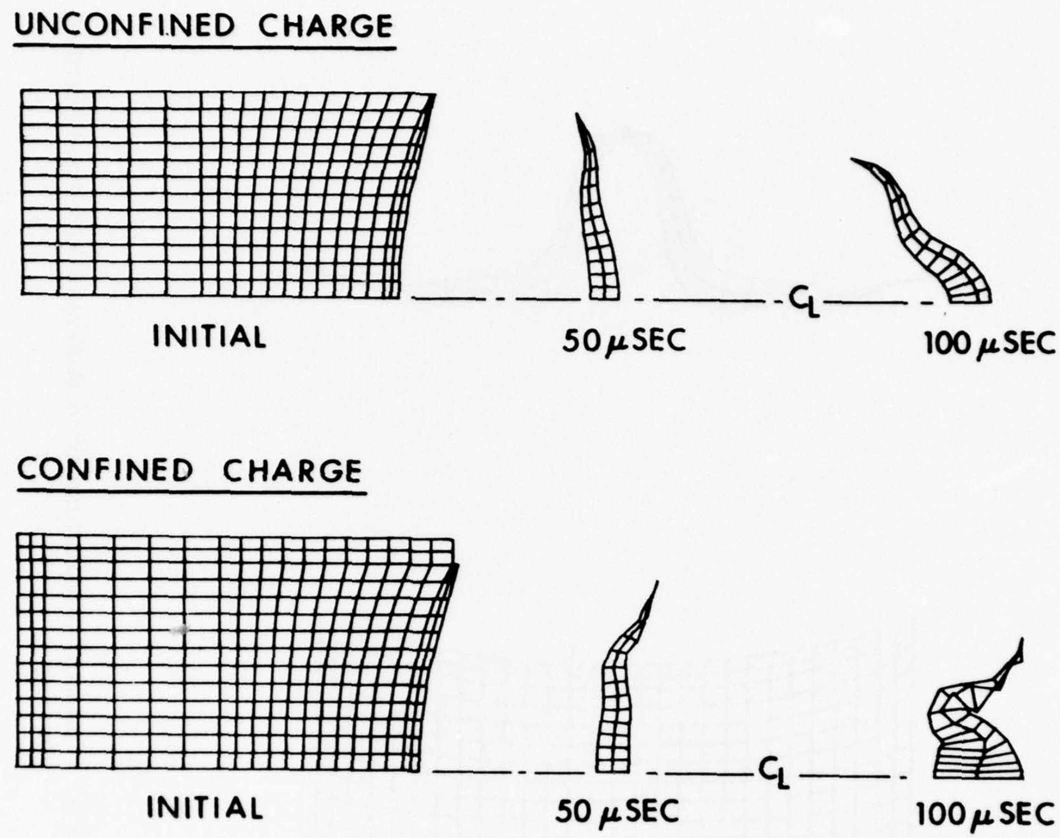

Figure 7. Computer Simulation of the Performance of a Unconfined and Confined Ballistic Disc Device

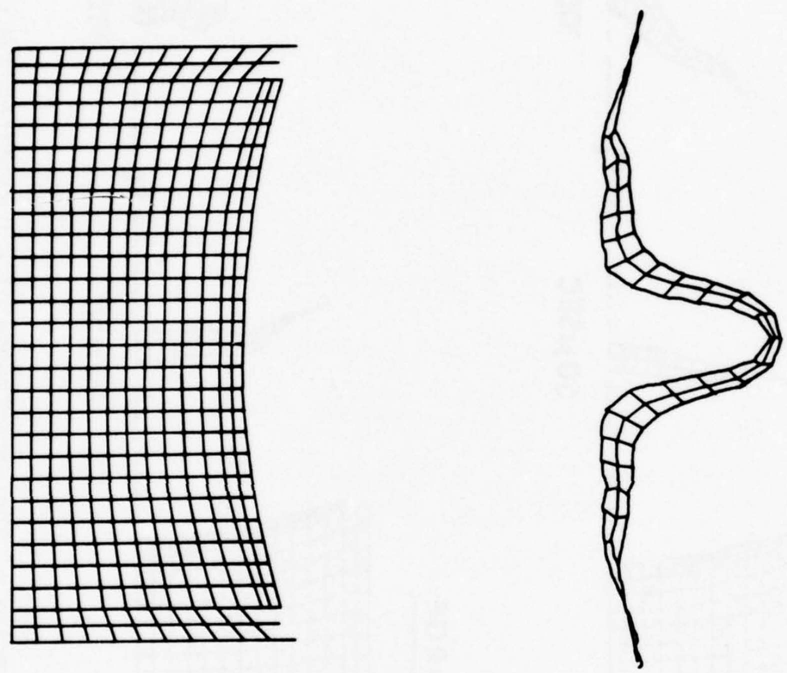

Figure 8. Computer Simulation of a Modified Misznay-Schardin Device

Figure 9 shows, at 50μsec after initiation, both the speed distribution and projection angle distribution as a function of radial position for three different designs. The solid curve (unconfined) shows these distributions for the ballistic disc configuration shown in Figure 6. This configuration exhibits no substantial break up and forms a desired projectile shape. The solid curve (confined) gives this information for the confined ballistic disc design shown in Figure 7. This configuration breaks up into several pieces resulting in poor performance. Notice the difference between these two cases, especially the difference in projection angles at this point. A series of computer runs, out to 50 microseconds, was made in an attempt to obtain a design which has, at that time, velocity distributions similar to the ballistic disc design (solid, unconfined curve). The resulting design is indicated by the dashed line in Figure 9. The projection angle distribution is similar to the desired distribution. The speed distribution, while being lower in magnitude, has the desired shape. This design was tested, and break up of the liner occurred.

The liner designs are shown in Figure 9. The new design (dashed) is substantially thicker than the ballistic disc over the outer portion. This thickness increase is required to offset the general pressure increase caused by the added lateral confinement. The use of a finite-difference code resulted in a design which is correct with respect to inertial properties. Structurally, however, the liner design may not be able to accommodate the deformation necessary to produce the desired projectile shape. Experiments show the liner fractures under this deformation. This inadequacy may possibly be overcome by laminating the liner or by using a material which will withstand larger deformations.

It should be noted that the code can calculate both the stress and strain distribution occurring within the liner. However, without a reliable rule to predict material fracture, this information does not directly help the designer. A reliable method to predict fracture would substantially increase the utility of a finite-difference code for computer aided design studies.

C. Shaped Charge Warheads

We have applied the HEMP code to shaped charge problems to see if useful information can be obtained from these Lagrangian calculations. Figure 10 illustrates a simulation of a wide angle shaped charge (120° apex angle). In this calculation, the explosive was confined on its periphery by a steel casing. The calculated liner shape is shown at 18 microseconds after explosive initiation, and the calculated tip velocity is in good agreement with the measured value. Also shown in Figure 10 is a radiographic observation of a similar, but unconfined, shaped charge at about the same time. The calculations could be carried out to a later time, but the accuracy of those calculations would be questionable since many zones are quite distorted at 18 microseconds. Since

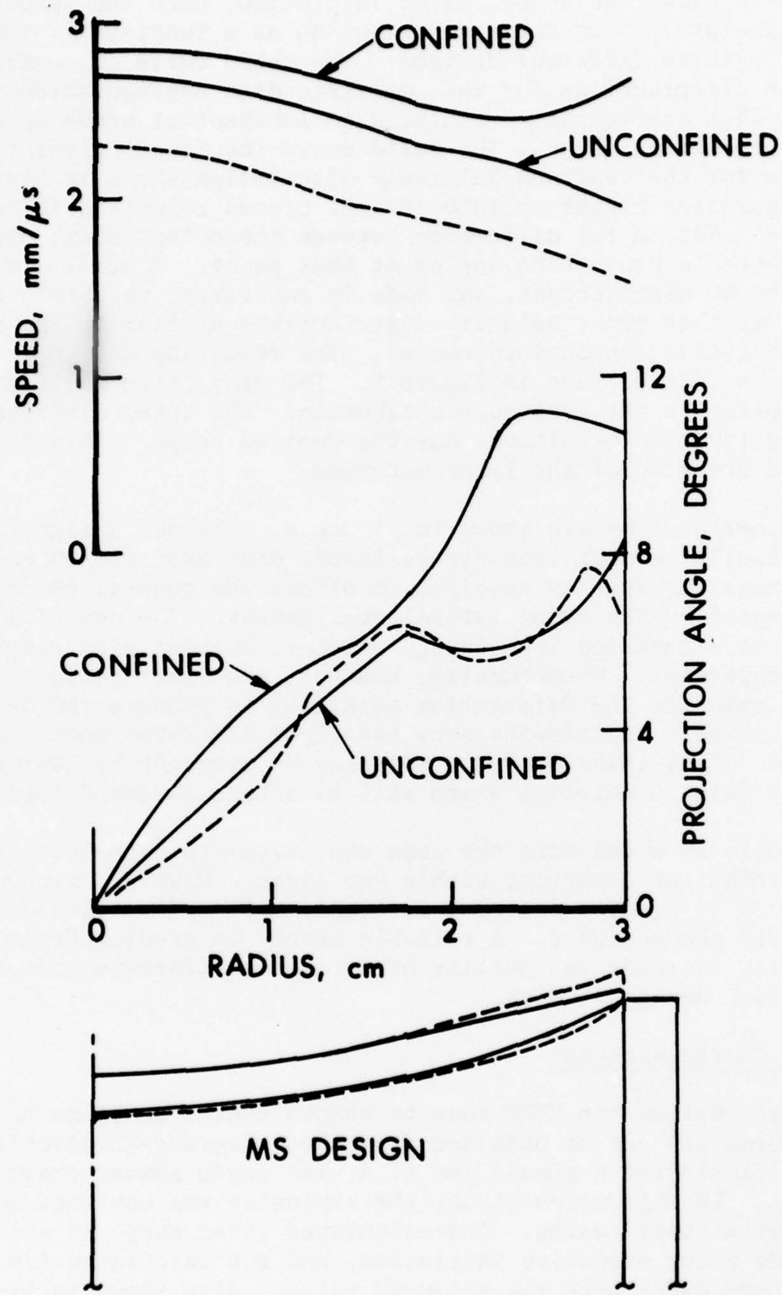

Figure 9. Speed and Projection Angle Distributions Calculated with the HEMP Code (The solid curve refers to the Ballistic Disc Design, and the dashed curve refers to the modified configuration)

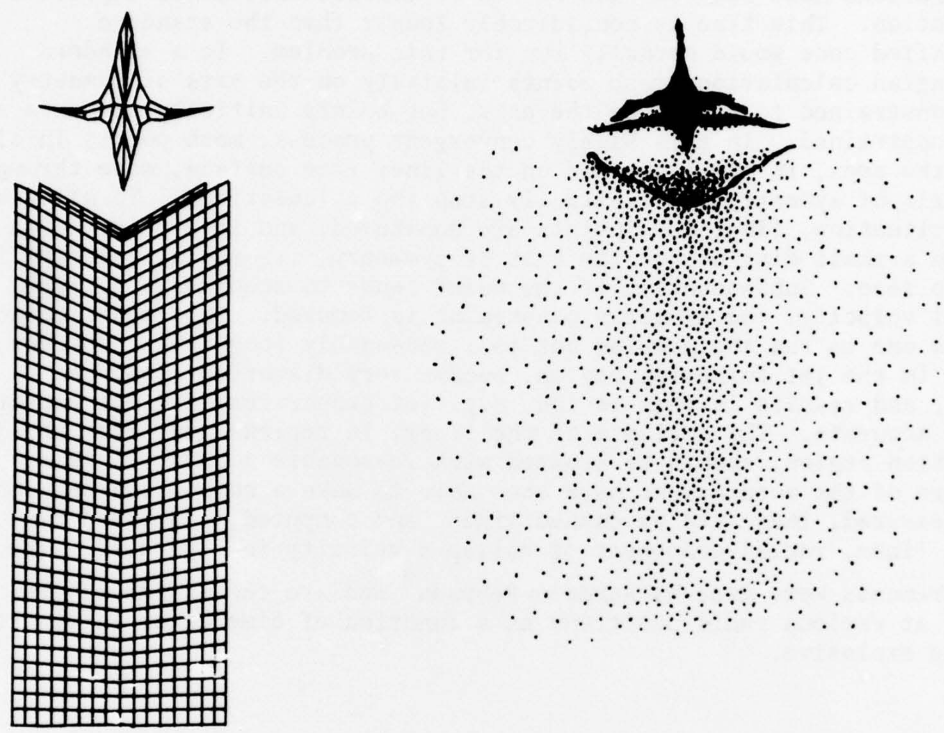

Figure 10. Simulation of a Wide Angle Shaped Charge Compared with a Radiographic Observation (The calculation on the left applies to a confined configuration while the radiographic tracing on the right applies to an unconfined charge)

this design produces a jet which is several inches long, these calculations do not provide much information about the properties of the jet. A relatively simple rezoning technique might be used to provide much more information about problems of this type.

Figure 11 represents the simulation of a conventional 42° copper cone, composition B loaded, shaped charge. This charge design, along with some performance measurements, is described in Reference 8. These calculations have been carried out to 30 microseconds after explosive initiation. This time is considerably longer than the standard unmodified code would normally run for this problem. In a standard Lagrangian calculation, mesh points initially on the axis of symmetry are constrained to remain on the axis, but points initially off axis are not constrained. In this highly convergent process, mesh points initially near the apex, in the liner and on the liner free surface, move through the axis of symmetry and eventually stop the calculations. To alleviate this situation, liner mesh points are monitored, and if a point moves to within a small distance of the axis of symmetry, its radial velocity is set to zero. Subsequently, if the point tends to acquire an outward radial velocity, the symmetry constraint is removed. This modification allows one to run the problem out to a reasonably long time. However, zones in the jet formation region, become very distorted (long and thin), and results in this region, e.g. jet properties, are not expected to be accurate. The collapse of the liner, in regions away from the jet formation region, should be treated with reasonable accuracy. As a measure of the accuracy we have been able to make a comparison between the measured, indicated by dashed lines, and computed, indicated by solid lines, radial component of collapse velocity in Figure 12. The measurements were made by Randers-Pehrson[9] and are the inside of the liner at various radii positions as a function of time after initiation of the explosive.

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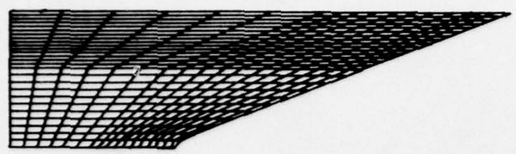
[8] *F. E. Allison and R. Vitali, "An Application of the Jet-Formation Theory to a 105mm Shaped Charge," Ballistic Research Laboratories Report No. 1165, Aberdeen Proving Ground, MD, March 1962. (AD #277458)*

[9] *Private Communition from G. Randers-Pehrson, Picatinny Arsenal, New Jersey.*



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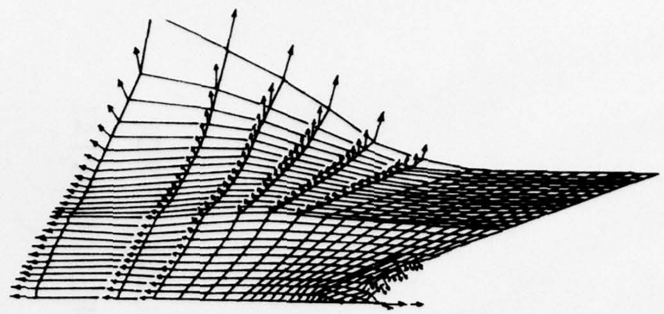

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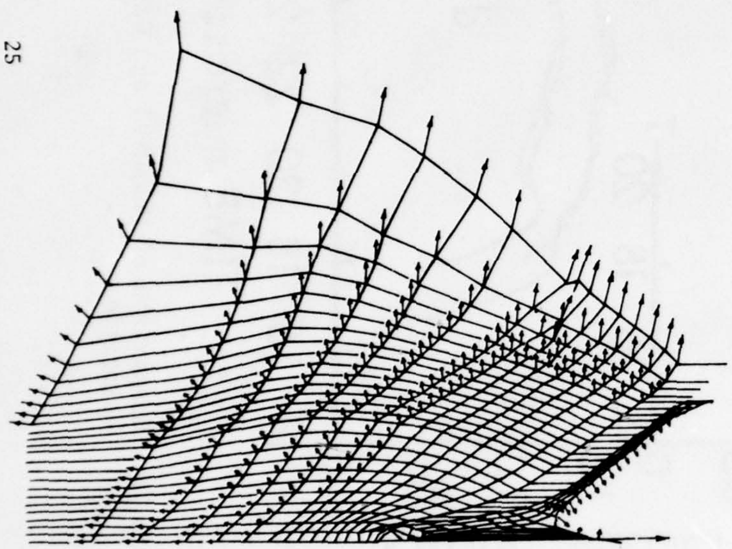

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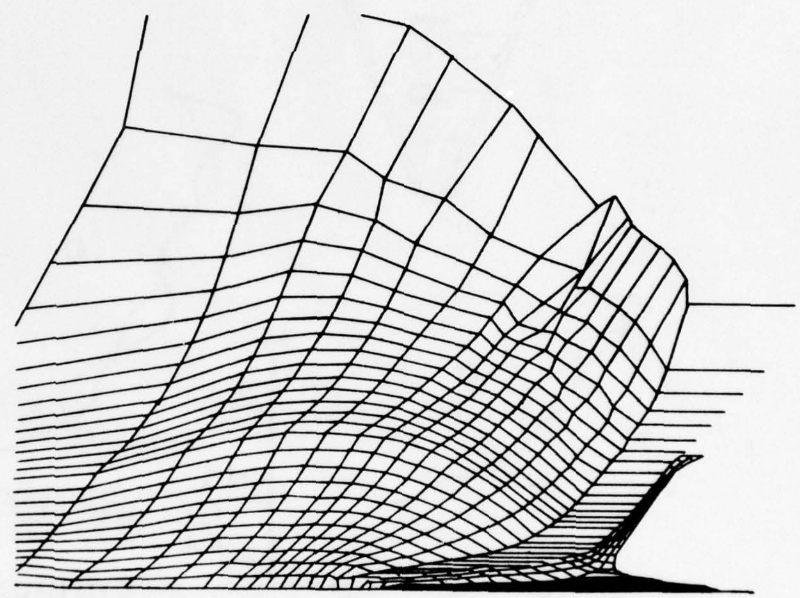

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Figure 11. Simulation of a Conventional Shaped Charge

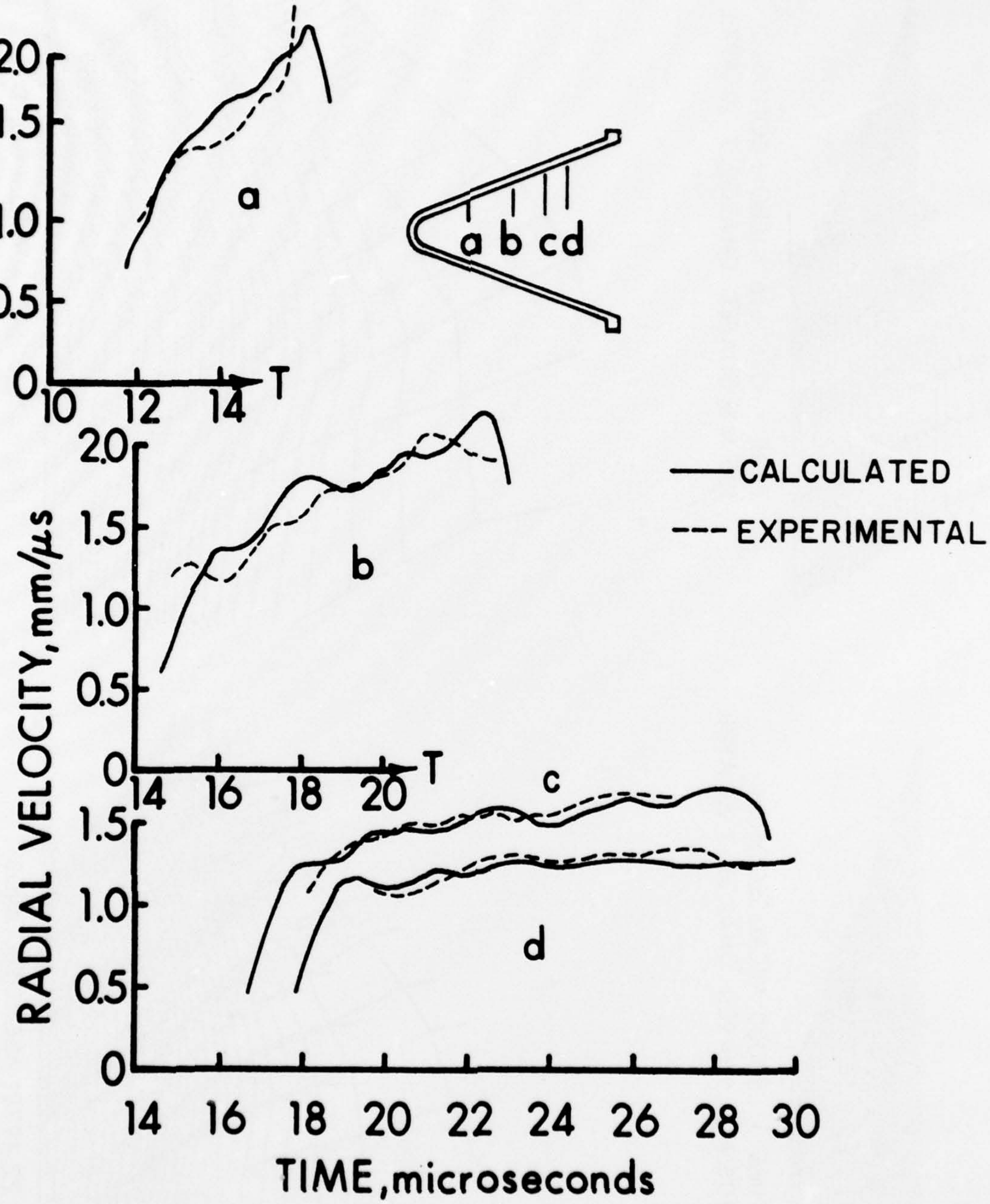

Figure 12. Comparison of Measured and Calculated Radial Collapse Velocities

Figure 13 shows the collapse velocity as a function of axial position from the virtual apex. This velocity is obtained from the row of mesh points along the middle of the liner, and it is chosen for each point at a time when the inward radial component is a maximum. These calculations indicate that the maximum collapse velocity comes from the central portion of the liner. The relatively low values from the apex portion occur because the liner becomes affected by the jet formation region before it can be accelerated to its potentially high collapse velocity. This effect has been noted by Simon and DiPersio[10] and by Kiwan and Wisniewski.[11]

Once the collapse velocity distribution is established, the jet formation theory of Pugh, Eichelberger and Rostoker[12] can be used to obtain the jet velocity, the jet mass, and other pertinent jet characteristics. The jet velocity distribution obtained from a version of this jet formation theory is also shown in Figure 13. The experimentally determined collapse and jet velocity distributions of Allison and Vitali[8] are also plotted in Figure 13. Good agreement exists between the experimental and calculated collapse velocity distributions. However, the jet velocity distribution is very sensitive to the shape of the collapse velocity curve; therefore, the jet velocity calculated from the collapse velocity is not very accurate.

III. SUMMARY

Fragment velocity (speed and direction) distributions calculated with the HEMP code agree well with experimental distributions from naturally fragmenting systems. A very simple modification to the code has been made in an attempt to model, at least approximately, the effect of fragmentation and leakage. If this effect is not included, the calculations must be stopped at some arbitrary point, say an expansion ratio of 3, or the estimated velocity will tend to be high. The calculated velocity will continue to rise if the casing is treated as continuous. At the present time, the expansion ratio corresponding to

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[10] *R. Dipersio and J. Simon, "An Experimental Method of Obtaining Collapse Velocity of the Inner Walls of a Linear Shaped Charge Liner," Ballistic Research Laboratories Memorandum Report No. 1969, September 1965. (AD #688601)*

[11] *A. Kiwan and H. Wisniewski, "Theory and Computations of Collapse and Jet Velocities of Metallic Shaped Charge Liners," Ballistic Research Laboratories Report No. 1620, November 1972. (AD #907161L)*

[12] *E. M. Pugh, R. J. Eichelberger and N. Rostoker, "Theory of Jet Formation by Charges With Lined Conical Cavities," J. Appl. Phys. 23, 532, 1952.*

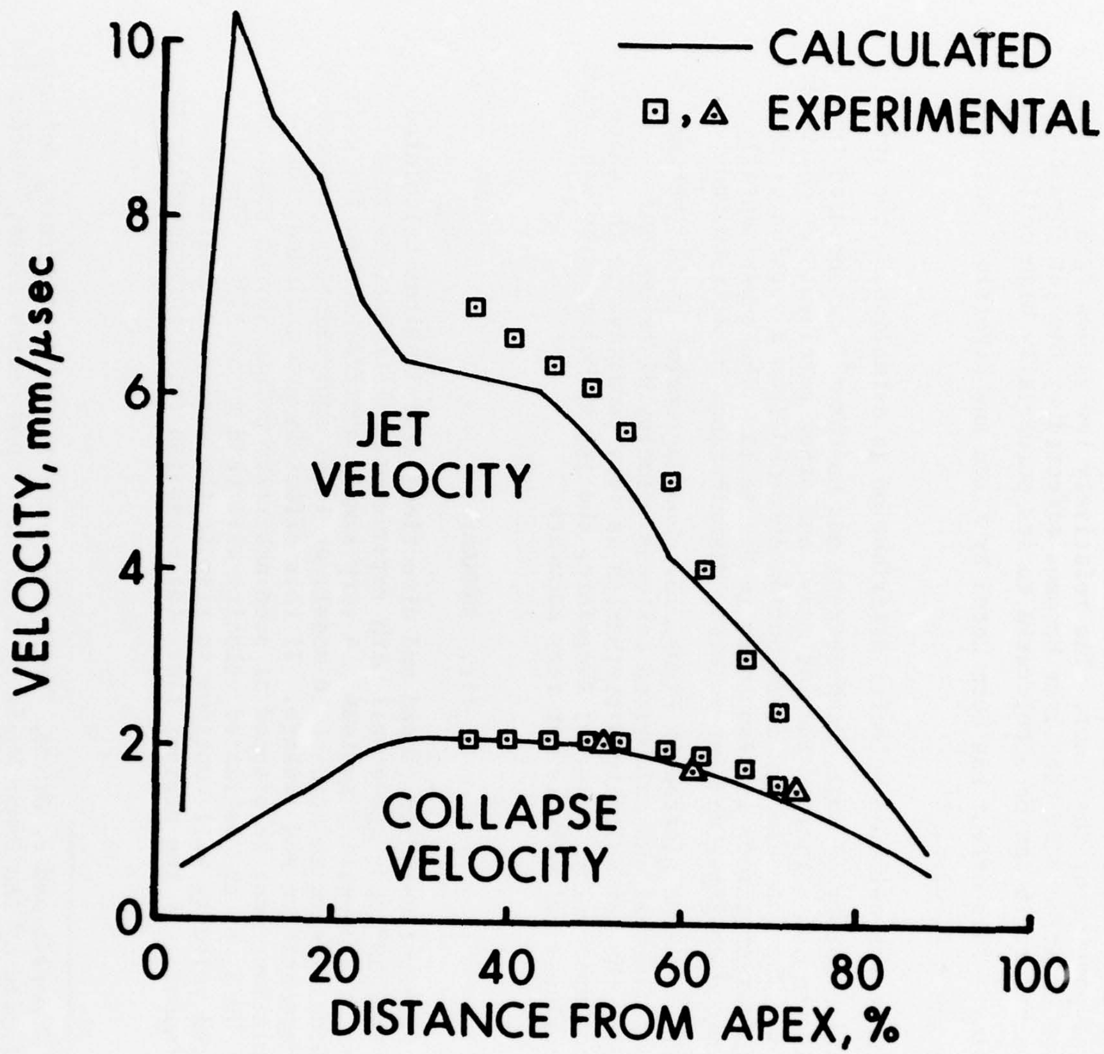

Figure 13. Calculated Collapse Velocity and Jet Velocity Distributions Compared with Experimental Data

fragmentation is input to the code. However, if a rule for fragmentation is incorporated into the code, the expansion ratio corresponding to fragmentation may be determined during the course of the numerical calculations. Also, this leakage model may be expanded to treat configurations containing preformed fragments.

The numerical simulation of a Misznay-Schardin device appears to be straightforward. This problem is ideally suited to Lagrangian code calculations, as opposed to Eulerian calculations, since the relative flow is small. The comparison with experiment is good. However, unless a reliable method of predicting liner break up can be incorporated into the code, its usefulness as a design tool is quite limited. One promising method of treating this break up has been described by Seaman, Barbee and Curran.[13]

By modifying the treatment of boundary conditions in the code, the collapse velocity distribution of a conventional shaped charge can be calculated. This calculated collapse velocity distribution agrees well with data obtained experimentally. One should note that, if the jet formation theory is to be used to determine jet characteristics, the collapse velocity distribution, both velocity and slope, must be very accurately determined since small changes in the distribution cause large changes in the jet characteristics. Also, in the region of positive slope, the standard jet formation equations should not be applied. Just how one should handle this region is not clear, especially since material interaction is important there. The velocity of approach is near sonic in that region, and one wonders how well the steady, incompressible relations model the flow. For penetration estimates, the tip velocity is the most important parameter, and the tip velocity is controlled by the region of positive slope.

Because of these considerations, we presently feel that data obtained from complete solutions to the shaped charge problem with an Eulerian code should be more reliable than the partial solution presented here. The only drawback to the Eulerian calculation is the long running time required (about 6 hours on the BRLESC computers).

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[13] *L. Seaman, T. Barbee and D. Curran, "Dynamic Fracture Criteria of Homogeneous Materials," Stanford Research Institute Technical Report No. ARWL-TR-71-156, Menlo Park, CA, December 1971.*

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